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Phenomenology of Light Gauginos

Glennys R. Farrar[1]

Department of Physics and Astronomy
Rutgers University, Piscataway, NJ 08855, USA

Abstract: I advocate the virtues of a very economical version of the minimal supersymmetric standard model which avoids cosmological problems often encountered in dynamical SUSY-breaking and solves the SUSY-CP problem. Imposing $m_Z = 91$ GeV and $m_t \sim 175$ GeV implies that scalar masses are generally $100 - 200$ GeV. The gluino and photino are massless at tree level. At 1-loop, the gluino mass is predicted to be in the range $m_{\tilde{g}} : 100 - 600$ MeV and the photino mass can be estimated to be $m_{\tilde{\gamma}} : 100 -$ 1400 MeV. New hadrons with mass $\sim 1\frac{1}{2}$ GeV are predicted and described. The "extra" flavor singlet pseudoscalar observed in two experiments in the $\iota(1440)$ region, if confirmed, is naturally interpreted as the state which gets its mass via the QCD anomaly. Its superpartner, a gluon-gluino bound state, generally has a lifetime longer than $5\ 10^{-11}$ sec and would not have shown up in existing searches. Search strategies and other consequences of the scenario are discussed.

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The customary approach to studying the phenomenological implications of supersymmetry has been to assume that the "low energy" effective Lagrangian below the SUSY-breaking scale, M_{SUSY}, contains all possible renormalizable operators, including in principle all possible soft supersymmetry breaking terms, consistent with the gauge symmetries and possibly some global and discrete symmetries. Some models of SUSY-breaking naturally lead to relations among the SUSY-breaking parameters at the scale M_{SUSY} so that the minimal supersymmetric standard model (MSSM) requires specification of 6-8 parameters beyond the gauge and Yukawa couplings already determined in the MSM: $tan\beta \equiv \frac{v_U}{v_D}$, the ratio of the two Higgs vevs, μ, the coefficient of the SUSY-invariant coupling between higgsinos, M_0, a universal SUSY-breaking scalar mass, m_{12}^2, the SUSY-breaking mixing in the mass-squared matrix of the Higgs scalars (aka μB or $\mu M_0 B$ in alternate notations), $M_{1,2,3}$, the SUSY-breaking gaugino masses (proportional to one another if the MSSM is embedded in a GUT), and A, the coefficient of SUSY-breaking terms obtained by replacing the fermions in the MSM Yukawa terms by their superpartners. To obtain predictions for the actual superparticle spectrum in terms of these basic parameters, the renormalization group equations for masses, mixings and couplings are evolved from the scale M_{SUSY} to the scale M_{Z^0} where on account of different RG running and flavor dependent couplings, the various scalars and fermions have quite different masses. A particularly attractive aspect of this approach is that for the heavy top quark which is found in nature[1, 2], the mass-squared of a combination of Higgs fields becomes negative at low energy and the electroweak symmetry is spontaneously broken[3, 4], with m_Z a function of A, M_0 and other parameters of the theory. In this conventional treatment of the MSSM, the lightest squark mass is constrained by experiment to be greater than 126 GeV and the gluino mass to be greater than 141 GeV[5].

I will argue here that a more restrictive form of low energy SUSY breaking is actually more plausible, one without dimension-3 operators. We shall

see that the remaining parameters of the theory are well-constrained when electroweak symmetry breaking is demanded, and that the resultant model (MSSM') is both extremely predictive and consistent with laboratory and cosmological observations. If this is the correct structure of the low energy world, there will be many consequences which can be discovered and investigated before the construction of the LHC. Some of these are discussed below.

There are at least two good reasons for dispensing with dimension-3 SUSY breaking operators in the low energy theory. In the most attractive SUSY-breaking scenario, hidden sector dynamical SUSY breaking, such operators make negligible contribution unless there is one or more *gauge singlet* field in the hidden sector whose auxilliary field gets a large vev. However it was shown in ref. [6] that SUSY breaking with hidden sector gauge singlets lead to particles with masses in the 100 GeV - 1 TeV region which are in conflict with cosmology, in particular causing late-time entropy production which is incompatible with primordial nucleosynthesis. Besides avoiding the problems associated with singlet fields, not having dimension-3 SUSY breaking is attractive because it solves the SUSY CP problem[2].

If there are no dimension-3 SUSY-breaking operators, A and $M_{1,2,3}$ are zero, and the gluino and lightest neutralino are massless in tree approximation. They get masses at one loop from virtual top-stop pairs, and, for the neutralinos, from "electroweak" loops involving wino/higgsino-Higgs/vector

[2]In this scenario, the only phases other than those associated with the strong CP problem (the phases in the quark mass matrix and θ parameter) which can be present in the theory at the scale M_{SUSY} appear in the parameters μ and m_{12}^2. However a combination of an R-transformation and U(1) transformations on the Higgs superfields allows these phases to be removed. Any phase which is introduced thereby into the Yukawa terms in the superpotential can be removed by chiral transformations on the quark superfields, merely changing the phases which contribute to the strong CP problem (which must be solved by some other mechanism). Since the gauge-kinetic terms are not affected by U(1) and R transformations, the preceding manipulations do not introduce phases in interactions involving gauginos. I thank Scott Thomas for pointing out how use of the R transformation simplifies the proof.

boson pairs[7, 8, 9]. The size of these corrections were estimated, for various values of M_0, μ, and $tan\beta$ in ref. [9]. There, it was determined that in order to insure that the chargino mass is greater than its LEP lower bound of about 45 GeV, μ must either be less than 100 GeV (and $tan\beta \lesssim 2$) or greater than several TeV. Here I will also demand that the electroweak symmetry breaking produces the observed m_Z for $m_t \sim 175$ GeV[1]. This is not possible in the large μ region, so I will consider only $\mu \lesssim 100$ GeV. In addition, from Fig. 6 of ref. [3] one sees that M_0, the SUSY-breaking scalar mass, must be $\sim 100 - 300$ GeV, with 150 GeV being the favored value. From Figs. 4 and 5 of ref. [9] this gives $m_{\tilde{g}} \sim 100 - 600$ and $m_{\tilde{\gamma}} \sim 100 - 900$ MeV. Since the electroweak loop was treated in ref. [9] with an approximation which is valid when M_0 or μ is $>> m_Z$, their results for the photino mass are only indicative of the range to be expected. Until a more precise calculation is available, we attach a $\sim$factor-of-two uncertainty to the electroweak loop, and consider the enlarged photino mass range $100 - 1400$ MeV.

The purpose of this Letter is to investigate the most essential aspects of the phenomenology of this theory, having restricted quite substantially the allowed ranges of parameters. The primary issues to be discussed are:

1. Predicted mass and lifetime of the lightest R-meson, the $g\tilde{g}$ bound state denoted R^0.

2. Predicted mass of the flavor singlet pseudoscalar which gets its mass via the anomaly (the "extra" pseudoscalar corresponding to the $\tilde{g}\tilde{g}$ ground state degree of freedom).

3. Identity of the flavor singlet pseudogoldstone boson resulting from the spontaneous breaking of the extra chiral symmetry associated with the light gluino.

4. The flavor-singlet R-baryon composed of $uds\tilde{g}$, called S^0.

5. Production rates and detection strategies for the new R-hadrons.

The R^0 lifetime is the most important item in this list. For many years the famous UA1 figure[10] and its decendants, showing the allowed regions of the gluino-squark mass plane, has widely been accepted as excluding all but certain small "windows" for low gluino mass. However this figure was constructed under the *assumption* that the gluino lifetime is short enough that missing energy and beam dump experiments are sensitive to it. As emphasized in ref. [11], R-hadrons produced in the target or beam dump degrade in energy very rapidly due to their strong interactions. However the photino is supposed to reinteract in the detector downstream of the beam dump or carry off appreciable missing energy. Only when it is emitted before the R-hadron interacts, will it typically have enough energy to be recognized. As discussed in connection with a particular experiment in ref. [11], and more generally in ref. [12], if the R^0 lifetime is longer than $\sim 5\ 10^{-11}$ sec this criterion is not met and beam dump and missing energy experiments become "blind" to light gluinos. Thus the commonly accepted notion of various tiny "windows" for light gluinos, is simply wrong for the case that R^0's have lifetimes longer than $\sim 5\ 10^{-11}$ sec.[3] Furthermore, the UA1 analysis accepted at face value a number of experiments searching for low-mass gluinos which were analyzed using perturbative QCD predictions which fail to make the important distinction between the current mass of the gluino and its constituent mass or the mass of the hadrons containing it. As will be clear after we find the R^0 mass in the massless gluino limit, this distinction is

[3] The cutoff in sensitivity as a function of $\tau_{\tilde{\gamma}}$, the characteristic timescale for photino emission, depends on the experiment; $5\ 10^{-11}$ is just a useful ballpark demarcation. Unfortunately, the acceptance of these experiments has not generally been reported in experimental terms, as a function of $\tau_{\tilde{\gamma}}$, $\sigma_{\tilde{g}}$ and $\sigma_{\tilde{\gamma}}$ (gluino production and photino rescattering cross sections). Instead results have been reported in terms of excluded regions in the $m_{\tilde{g}}$, m_{sq} plane, implicitly assuming that $\tau_{\tilde{\gamma}}$ is small enough for the gluino energy not to have been degraded before photino emission. Had the former information been reported, it would be possible to make a more quantitative statement on the allowed R^0 lifetime: since gluinos are produced primarily in R-mesons which decay quickly to an R^0[12], $\tau_{R^0} \approx \tau_{\tilde{\gamma}}$.

even more important than in the case of quarks. Ignoring it leads in some cases to a serious overestimate of the expected production rate, and thus an exagerated view of the experimental sensitivity.

In ref. [12] I reported the result of a comprehensive study of relevant experiments, including all those used in the UA1 analysis. The problems mentioned in the previous paragraph and the modifications they imply in the analysis of the excluded regions are discussed in detail in ref. [12]. Much of the low-mass region is only excluded when beam-dump experiments are applicable. Instead one finds (see Fig. 1, reproduced from ref. [12]) that an R^0 in the mass range ($\sim 1.1 - 1.5$ GeV) is consistent with the present experimental situation for any lifetime $\gtrsim 5\ 10^{-11}$ s. The mass range $\sim 1.5 - 1.8$ GeV is allowed for lifetimes between $\sim 5\ 10^{-11} - 10^{-8}$s or $\gtrsim 2 \times 10^{-6}$s. In the restrictive scenario under discussion, M_0 is rather well determined so we will try below to estimate the R^0 lifetime.

In order to estimate the R^0 lifetime, we need its mass. Fortunately, it can be quite well determined from existing lattice QCD calculations, as follows[12]. If the gluino were massless and there were no quarks in the theory (let us call this theory sQCD), SUSY would be unbroken and the R^0 would be in a degenerate supermultiplet with the 0^{++} glueball, G, and a 0^{-+} state I shall denote $\tilde{\eta}$, which can be thought of as a $\tilde{g}\tilde{g}$ bound state[4]. To the extent that quenched approximation is accurate for sQCD[5], the mass of the physical R^0 in the continuum limit of this theory would be the same as the mass of the 0^{++} glueball, which has been measured in quenched lattice QCD to be 1440 ± 110 MeV[13]. Including errors associated with unquenching the

[4]It is convenient to think of the states in terms of their "valence" constituents but of course each carries a "sea" so, e.g., the glueball may be better described as a coherent state of many soft gluons than as a state of two gluons. Knowledge of these aspects of the states is not needed for estimation of their masses.

[5]The 1-loop beta function is the same for sQCD as for ordinary QCD with 3 light quarks, so the accuracy estimate for quenched approximation in ordinary QCD, $10 - 15\%$, is applicable here.

quarks and gluinos, the G, R^0, and $\tilde{\eta}$ masses were estimated in ref. [12] to be 1440 ± 375 MeV[6]. Mixing with other flavor singlet pseudoscalars can shift the $\tilde{\eta}$ somewhat. For gluino masses small compared to the "confinement mass" of $\sim 1\frac{1}{2}$ GeV, one would expect the R^0 and $\tilde{\eta}$ masses to be insensitive to the gluino mass. Thus in the absence of a dedicated lattice gauge theory calculation of the masses of these particles, we can adopt the estimate, 1.4 ± 0.4 GeV for all these states, G, $\tilde{\eta}$, and R^0.

Having a reliable mass estimate is an important component in determining the phenomenology of a light gluino. Bag model estimates[14] were significantly lower than this, as they were for the glueball spectrum in comparison to lattice gauge theory. The fact that the R^0 mass is so much greater than even the vector meson masses, means that its production at low energies will be substantially kinematically suppressed compared to naive pQCD estimates. This fact, which was neglected in the UA1 analysis, was incorporated in the analysis of ref. [12].

Note that in sQCD, which is identical to ordinary QCD in quenched approximation, the $\tilde{\eta}$ with mass ~ 1.44 GeV is the pseudoscalar which gets its mass from the anomaly. Thus in QCD with light gluinos (QCD') the particle which gets its mass from the anomaly is too heavy to be the η'. Instead, the η' should be identified with the pseudogoldstone boson associated with the spontaneous breaking of the non-anomalous chiral U(1)[7] by the formation of $q\bar{q}$ and $\tilde{g}\tilde{g}$ condensates, $< \bar{q}q >$ and $< \bar{\lambda}\lambda >$. Using the usual PCAC and current algebra techniques, in ref. [12] I obtained the relationship between masses and condensates necessary to produce the correct η' mass (ignoring

[6]The uncertainty coming from unquenching both light quarks and gluinos was taken there to be 25%, however to the extent that the estimate of the quenching error for ordinary QCD is obtained by comparing lattice results with the hadron spectrum, that will already include the effects of gluinos if they are present in nature, and the ± 375 MeV uncertainty should be replaced by ± 240 MeV.

[7]Formed from the usual chiral U(1) of the light quarks and the chiral R-symmetry of the gluinos[12].

mixing): $m_{\tilde{g}} < \bar{\lambda}\lambda > \quad \sim 10\ m_s < s\bar{s} >$. The required gluino condensate is reasonable, for $m_{\tilde{g}} \gtrsim 100$ MeV[8]. In a more refined discussion, the physical η' would be treated as a superposition of the pseudo-goldstone boson and the orthogonal state which gets its mass from the anomaly. The important point, independent of details of the mixing, is that this scenario *predicts* the existance of a flavor singlet pseudoscalar meson in addition to the η' which is not a part of the conventional QCD spectrum of quark mesons and glueballs, whose mass should be $\sim 1.4 \pm 0.4$ GeV. I have not yet identified any clear test for the prediction that the η' is mainly a pseudogoldstone boson and probably contains a $\sim 30\%$ $\tilde{g}\tilde{g}$ component, since model independent predictions concerning the η' are for ratios in which the gluino component plays no role.[9]

Having in hand an estimate of the R^0 mass and photino mass, we now return to determining the R^0 lifetime. Making an absolute estimate of the lifetime of a light hadron is always problematic. Although the relevant short distance operators can be accurately fixed in terms of the parameters of the Lagrangian, hadronic matrix elements are difficult to determine. It is particularly tricky for the R^0 in this scenario because the photino mass is larger than the current gluino mass and, since $m_{\tilde{\gamma}} \sim \frac{1}{2} m_{R^0}$, the decay is highly suppressed even using a constituent mass for the gluino. The decay rate of a free gluino into a photino and massless $u\bar{u}$ and $d\bar{d}$ pairs is known[15]:

$$\Gamma_0(m_{\tilde{g}}, m_{\tilde{\gamma}}) = \frac{\alpha \alpha_s m_{\tilde{g}}^5}{48 \pi M_{sq}^4} \frac{5}{9} f(\frac{m_{\tilde{\gamma}}}{m_{\tilde{g}}}), \tag{1}$$

taking M_{sq} to be a common up and down squark mass. The function $f(y) = [(1-y^2)(1+2y-7y^2+20y^3-7y^4+2y^5+y^6)+24y^3(1-y+y^2)log(y)]$

[8]Ensuring $m_{\tilde{g}} \gtrsim 100$ requires $M_0 \lesssim 300$ GeV[9]. This is consistent with the values indicated by electroweak symmetry breaking for $m_t = 175$ GeV.

[9]Chiral perturbation theory implies characteristic relations between various physical quantities involving pseudogoldstone bosons. Whether it can be used here, given the large mass of the η', is under investigation. GRF and M. Luty, in preparation.

contains the phase space suppression which is important when the photino is massive. The problem is to take into account how interactions with the gluon and "sea" inside the R^0 "loans" mass to the gluino. If this effect is ignored one would find the R^0 to be absolutely stable except in the upper portion of its estimated mass range.

A method of estimating the *maximal* effect of such a "loan", and thus a lower limit on the R^0 lifetime, can be obtained by elaborating a suggestion of refs. [16, 17]. The basic idea is to think of the hadron as a bare massless parton (in this case a gluon) carrying momentum fraction x and a remainder (here, the gluino) having an effective mass $M\sqrt{1-x}$, where M is the mass of the decaying hadron, here the R^0. Then the structure function, giving the probability distribution of partons of fraction x, also gives the distribution of effective masses for the remainder (here, the gluino). Summing the decay rate for gluinos of effective mass $m(R^0)\sqrt{1-x}$ over the probability distribution for the gluino to have this effective mass, leads to a crude estimate or upper bound on the rate:

$$\Gamma(m(R^0), z) = \Gamma_0(m(R^0), 0) \int_0^{1-z^2} (1-x)^{\frac{5}{2}} F(x) dx f(z/\sqrt{1-x}), \qquad (2)$$

where $z = \frac{m_{\tilde{\gamma}}}{m(R^0)}$. The distribution function of the gluon in the R^0 is unknown, but can be bracketed with extreme cases: the non-relativistic $F_{nr}(x) = \delta(x - \frac{1}{2})$ and the ultrarelativistic $F_{ur}(x) = 6x(1-x)$. The normalizations are chosen so that half the R^0's momentum is carried by gluons. Figure 2 shows the R^0 lifetime produced by this model, for $M_{sq} = 150$ GeV and $m(R^0) = 1.5$ GeV, for these two structure functions, and also for the intermediate choice $F_{10}(x) = N_{10} x^{10}(1-x)^{10}$, as a function of $r \equiv z^{-1} = \frac{m(R^0)}{m_{\tilde{\gamma}}}$. Results for any R^0 and squark mass can be found from this figure using the scaling behavior $\Gamma(m(R^0), M_{sq}, z) \sim m(R^0)^5 M_{sq}^{-4} g(z)$, as long as it is legitimate to ignore the mass of the remnant hadronic system, say a pion.

The decay rates produced in this model can be considered upper limits on the actual decay rate, because the model in some sense maximizes the

"loan" in dynamical mass which can be made by the gluons to the gluino. For kaon semileptonic decay (where the $K_{\mu 3}$ mode would be strongly suppressed or excluded in the absence of similar effects, since the strange quark current mass is of the same order as the muon mass) this model gives the correct ratio between $K_{\mu 3}$ and K_{e3} rates, and rates 2-4 times larger than observed: overestimating the rate as we anticipated, but not by a terribly large factor. Although a large range of uncertainty should be attached to the R^0 lifetime estimated this way, these results are still useful because they give lower bounds on the lifetime. We can see that the beam dump experiments[18, 19, 20, 21] are unlikely to have been sensitive to the R^0. Even with the ultrarelativistic wavefunction which gives the shortest lifetime estimate, for most of the parameter space of interest the lifetime is not short enough for the R^0 to have decayed before its energy is degraded by interactions in the dump, which requires $\tau(R^0) \lesssim 5 \times 10^{-11}$[12].

There is another interesting light R-hadron besides the R^0, namely the flavor singlet scalar baryon $uds\tilde{g}$ denoted S^0. In view of the very strong hyperfine attraction among the quarks[22], this state may be similar in mass to the R^0.[10] If its mass is $\sim 1\frac{1}{2}$ GeV, it will be extremely long lived, or even stable if $m(S^0) - m(p) - m(e^-) < m_{\tilde{\gamma}}$. Even if decay to a photino and nucleon is kinematically allowed, the decay rate will be very small since it requires a flavor-changing-neutral transition as well as an electromagnetic interaction. If the S^0 does not bind to nuclei, its being absolutely stable is not experimentally excluded[22, 12]. There is not a first-principles understanding of the intermediate-range nuclear force, so that it is not possible to decide with certainty whether the S^0 will bind to nuclei. However the two-pion-exchange force, which is attractive between nucleons but insufficient to explain their

[10]It is amusing that the (spin 1/2) baryon spectrum contains an anomalous state, the $\Lambda(1405)$, which this discussion suggests is likely to be a uds-gluon flavor singlet cryptoexotic baryon. The validity of this suggestion for identity of the $\Lambda(1405)$ is of course independent of the existance of light gluinos.

binding[11], is repulsive in this case[12] because the mass of the intermediate R_Λ or R_Σ is much larger than that of the S^0.[12] For further discussion of the S^0 and other R-hadrons see refs. [22] and [12].

We have seen above that existing searches for gluinos and R-hadrons do not exclude this scenario, but it is also commonly claimed that light photinos are excluded. However those arguments do not apply to the case at hand. First of all, since gaugino masses come from radiative corrections, limits relying on GUT tree-level relations between gaugino masses do not apply. Furthermore, the lightest and next-to-lightest neutralinos (called in general χ_1^0 and χ_2^0) are not produced in Z decays with sufficient rate to be observed at LEP, because in this scenario the χ_1^0 is extremely close to being pure photino[9]. It contains so little higgsino that $Z^0 \to \chi_1^0\chi_1^0$ and $Z^0 \to \chi_1^0\chi_2^0$ are suppressed compared to the conventional scenario with tree-level gaugino masses, while the mass of the χ_2^0 is high enough that its pair production is too small to be important for most of parameter space.

It has also been claimed that a stable photino with mass less than 10 GeV is excluded because it would produce too large a relic abundance, "overclosing" the universe. These calculations assumed that self annihilation was the only important mechanism for keeping photinos in thermal equilibrium, leading to freeze out at a temperature $T \sim \frac{1}{14} m_{\tilde{\gamma}}$, below which the self-annihilation rate is less than the expansion rate of the universe. However it has recently been shown[24] that when the gluino is also light, other processes

[11] So that an ad hoc phenomenological σ exchange is postulated, which does not however correspond to any observed particle. I am indebted to R. Amado for discussions of this point.

[12] If its decay to a nucleon is kinematically forbidden, the S^0 would be absolutely stable unless both R-parity and baryon-number conservation are violated. In some models of R-parity violation[23], R-parity is violated in association with lepton number violation, but baryon number is conserved. In this case the photino would be unstable (e.g., $\tilde{\gamma} \to \nu\gamma$) but the S^0 stable. Stable relic S^0's could make up part of the missing mass in our galaxy, but since they have strong interactions they would clump too much to account for the bulk of the missing dark matter of the universe. I thank E. Kolb for discussions on this matter.

involving $\tilde{\gamma} - R^0$ interconversion and R^0 self-annihilation become important, and freezeout is delayed to a lower temperature. When the ratio $r = \frac{m(R^0)}{m_{\tilde{\gamma}}}$ is in the range 1.2 - 2.2, the relic photino abundance can account for the dark matter of the universe[24]. Only when $r \gtrsim 2.2$ would the photino relic density be too large. If that were the case, R-parity would have to be violated, so that the photino is not absolutely stable, in order for this scenario to be viable.

Let us turn now to discovery strategies for the R^0 and S^0. With improvements in the determination of the MSSM' parameters by careful study of the renormalization group and ew symmetry breaking constraints[13], and use of exact 1-loop radiative corrections[8] rather than the approximate ones of ref. [9], it should be possible to rather precisely predict the photino and gluino masses. Lattice gauge calcuations without quenched approximation could give the R^0 mass well enough to test whether the ratio $r = \frac{m(R^0)}{m_{\tilde{g}}}$ can lie in the range 1.2-2.2 needed to explain the dark matter[24]. The R^0 lifetime can be estimated using lattice gauge theory, which should be much more satisfactory than the model developed above, to compute the hadronic matrix elements of the short distance operators. It will take some time for all these things to be done, so that for the present we should consider discovery strategies in the two cases: that it can be discovered via its decay, or it is too long lived for that.

In ref. [12] I discussed strategies for detecting or excluding the existance of an R^0 with a lifetime so long that it only rarely decays in the apparatus. If instead the R^0 lifetime is in the $\sim 10^{-7} - 5 \times 10^{-11}$s range, it should be possible to take advantage of the several very high-intensity kaon beams and the rare kaon decay and ϵ'/ϵ experiments, to find evidence for the R^0. It is fortuitous that the kaon experiments often run with and without regenerator, and the K^0_L and K^0_S lifetimes are comparable to the lifetimes of interest for the R^0,

[13] GRF and C. Kolda, in preparation.

allowing a large portion of the relevant range of lifetimes to be probed. The beams for such experiments contain R^0's, whose decays one wants to observe. While R^0 production crossections can be reliably computed in perturbative QCD when the R^0's are produced with $p_\perp \gtrsim 1$ GeV, high-luminosity neutral kaon beams are produced at low $p_\perp$ so pQCD cannot be used to estimate the R^0 flux in the beam. In this situation, a conservative lower bound on the production cross section could be the production cross section of $\bar{\Xi}$, at least for $m(R^0) \sim 1.4$ GeV.

The momentum in the R^0 rest frame of a hadron, h, produced in the two body decay $R^0 \to \tilde{\gamma} + \ h$, is:

$$P_h = \frac{\sqrt{m_R^4 + m_{\tilde{\gamma}}^4 + m_h^4 - 2m_R^2 m_{\tilde{\gamma}}^2 - 2m_{\tilde{\gamma}}^2 m_h^2 - 2m_h^2 m_R^2}}{2m_R}. \quad (3)$$

This falls in the range 300-800 MeV when $h = \pi^0$, for the mass ranges of interest: 1.2 GeV $< m_R <$ 1.7 GeV and 0.2 GeV $< m_{\tilde{\gamma}} <$ 0.9 GeV. Therefore, unless the R^0 is in the extreme high end of its mass range and the photino is in the low end of its estimated mass range, final states with more than one hadron will be significantly suppressed by phase space[14]. A particularly interesting decay to consider is $R^0 \to \eta\tilde{\gamma}$.[15] Since $m(\eta) = 547$ MeV $>$ $m(K^0) = 498$ MeV, there would be very little background mimicking η's in a precision K-decay experiment, so that detecting η's in the decay region of one of these experiments would be strong circumstantial evidence for an R^0. Since the R^0 is a flavor singlet and the $\tilde{\gamma}$ is a definite superposition of isosinglet and isovector, the relative strength of the $R^0 \to \pi^0\tilde{\gamma}$ and $R^0 \to \eta\tilde{\gamma}$ matrix elements is determined by Clebsches and is $9:1$. Thus the branching fraction of the $\eta\tilde{\gamma}$ decay mode is about 10%, in the most favorable case that multibody decay modes, and phase space suppression of the η relative

[14]For instance the final state $\pi^+\pi^-\pi^+\pi^-\tilde{\gamma}$ suggested by Carlson and Sher, while certainly distinctive, has a very small branching ratio for practically all the masses under consideration.

[15]I thank W. Willis for this suggestion.

to the π^0, are unimportant. If η's are detected, the Jacobian peak in the η transverse momentum, which occurs at $p_\perp \approx P_\eta$ defined in eq. (3) above, gives both a confirming signature of its origin, and provides information on the R^0 and $\tilde{\gamma}$ masses. The main issue in this search is clearly resolution. For long lifetimes, efficiency and precise kinematic reconstruction are the principle concerns. The sensitivity for short lifetimes is dependent on good resolution of the longitudinal location of the decay, to make sure one is not seeing η's produced in the regenerator. It seems that the generation of kaon experiments which will be running in the next year or so will be able to make this search[16].

Taking seriously the possibility that photinos account for the cold dark matter of the universe leads us to be particularly interested in the possibility that $r = \frac{m_R}{m_{\tilde{\gamma}}} \lesssim 2.2$. Fig. 3 shows how P_h depends on r, from which we see that in the region of interest the $R^0 \rightarrow \tilde{\gamma}\eta$ decay is considerably kinematically suppressed compared to $R^0 \rightarrow \tilde{\gamma}\pi^0$. Thus it would be very attractive to also be able to identify the latter reaction in the kaon decay experiments. This is much more demanding technically, but may be essential. Given measurements of $p_\perp^{max}$ in both $R^0 \rightarrow \tilde{\gamma}\eta$ and $R^0 \rightarrow \tilde{\gamma}\pi^0$, one could obtain at least a rough estimate of r, testing the dark matter possibility. This is because when $\frac{m_\eta^4 - m_\pi^4}{4 m_R^4} << 1$, eq. (3) leads to $P_\pi^2 - P_\eta^2 \approx \frac{1}{2}(1 + \frac{1}{r^2})(m_\eta^2 - m_\pi^2)$, allowing r to be extracted.

Light gluinos have many indirect consequences. None of them are presently capable of settling the question as to whether light gluinos exist, since they all rely on understanding non-perturbative aspects of QCD. So far, our assessment of the inherent theoretical uncertainty of QCD predictions is founded on the quality of the agreement between models and data. If the true theory is not QCD but, say, QCD', this will lead to an underestimate of the uncertainty in the predictions, since the models are tuned to agree with data

[16]I. Manelli and S. Somalwar, private communications.

assuming the validity of standard QCD without gluons. Nonetheless it is interesting to recall some phenomena sensitive to differences between QCD and QCD':

1. The running of α_s is different with and without light gluinos. In principle this can be investigated comparing α_s determined at different scales, e.g., from deep-inelastic scaling, and at the τ, Υ and Z^0. There are pitfalls, but progress is being made. See [12] for discussion and references. Less susceptible to modeling errors and very promising when the fermionic determinant can be computed precisely enough, will be to use consistency between data and lattice gauge calculations of quarkonia spectra, with and without light gluinos[17].

2. Jet production at FNAL and LEP is different with and without light gluinos. Since gluinos in this scenario are long enough lived that they hadronize before decaying to a photino, they produce jets similar to those produced by the other light, colored quanta: gluons and quarks[25]. In Z^0 decay, only 4- and more- jet events are modified; the magnitude of the expected change is smaller than the uncertainty in the theoretical prediction. Calculation of the 1-loop corrections to the 4-jet amplitudes would allow the theoretical uncertainty to be reduced sufficiently that data might be able to discriminate between QCD and QCD'[25]. In $p\bar{p}$ collisions, there is a difference already in 1-jet cross sections[25]. However absolute predictions are problematic since they rely on structure functions which have been determined assuming QCD, not QCD'. This could be improved, but probably would have large uncertainties. More promising might be to search for differences in the expected *relative* n-jets cross sections[25].

In summary, this paper has investigated the phenomenological conse-

[17]S. Shenker, private communication.

quences of a restrictive form of SUSY breaking which is theoretically attractive because it avoids cosmological problems associated with gauge singlet fields and solves the SUSY CP problem. Paramters of the theory were constrained by requiring correct electroweak symmetry breaking, and masses and lifetimes of particles were estimated. The main conclusions, including some results obtained in refs. [12, 9, 24], are the following:

- Gluino mass is 100-600 MeV; photino mass is $\sim 100 - 1400$ MeV; lightest chargino has a mass less than m_W; squark and slepton masses will be of order 100-200 GeV[18]; the μ parameter is $\lesssim 100$ GeV and $tan\beta \lesssim 2$.

- The lightest R-hadron is probably the R^0, with mass $\sim 1.4 \pm .3$ GeV and lifetime $\gtrsim$ few $\times 10^{-10}$s, possibly much longer. The decay mode $R^0 \rightarrow \eta\tilde{\gamma}$ can have a branching fraction of up to about 10%. Finding evidence of η production in an intense neutral kaon beam, with missing $p_\perp$ having a jacobian peak characteristic of a two body decay, would be a spectacular signal of this scenario. For $m_{\tilde{\gamma}} \gtrsim \frac{1}{2} m(R^0)$, the decay $R^0 \rightarrow \pi^0\tilde{\gamma}$ is optimal, albeit very challenging experimentally. Some possibilities if the R^0 has too long a lifetime for detection through its decay are discussed in ref. [12].

- The lightest color-singlet supersymmetric particle, the photino, is an excellent cold dark matter candidate if $r \equiv \frac{m(R^0)}{m_{\tilde{\gamma}}}$ has a critical value

[18]Conventional squark limits do not apply when the gluino is light and long-enough-lived to hadronize, as in this scenario. Here, the relevant signal will be a peak in the invariant mass distribution of a pair of jets, because squarks decay via $S_q \rightarrow \tilde{g}q$. It is reasonable to expect that the squarks associated with the u, d, s, c and b quarks will be approximately degenerate, while the stop will be significantly heavier. Moreover the cross section for producing a squark pair of each flavor will be comparable within about a factor of two with the cross section for producing a pair of heavy quarks of that mass. From the calculated production rates for $t\bar{t}$ it is clear that there should be a substantial number of events containing squark pairs at FNAL, up to quite high squark mass. A search for events in which *two* pairs of jets reconstruct to the same invariant mass should be made.

in the range 1.2 - 2.2[24]. This is consistent with the masses expected in the present scenario. If the R^0 is discovered, determining its lifetime and photino-production cross sections will allow a much more precise computation of the critical value of r. This would allow confirmation or refutation of the proposal of ref. [24], that relic photinos are responsible for the bulk of the missing matter of the Universe.

- There should be a flavor-singlet pseudoscalar with mass $\sim 1.4 \pm .4$ GeV, in addition to the mesons and glueballs of the conventional QCD spectrum. The MarkIII[26] and DM2[27] experiments find evidence for two flavor singlet pseudoscalars and one vector in the $\iota(1440)$ region, where only one pseudoscalar is expected in ordinary QCD. With its much greater statistical power, the Beijing collider should be able to definitively determine the resonance structure of this region. Establishing the predicted extra pseudoscalar would be a strong boost for the scenario advocated here.

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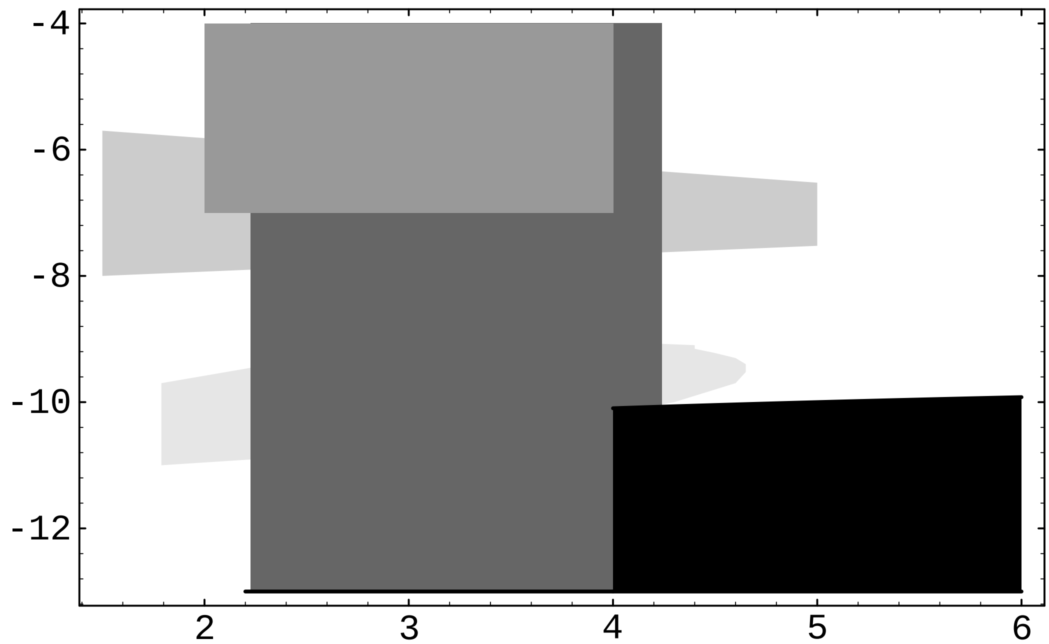

Figure 1: Figure showing the experimentally excluded regions of $m(R^0)$ and $\tau_{\tilde{g}}$. Horizontal axis is $m(R^0)$ in GeV beginning at 1.5 GeV; vertical axis is Log_{10} of the lifetime in sec. A massless gluino would lead to $m(R^0) \sim 1.4 \pm .4$ GeV. ARGUS and Bernstein et al give the lightest and next-to-lightest regions (lower and upper elongated shapes), respectively. CUSB gives the next-to-darkest block; its excluded region extends over all lifetimes. Gustafson et al gives the smaller (mid-darkness) block in the upper portion of the figure; it extends to infinite lifetime. The UA1 experiment the darkest block in the lower right corner; it extends to higher masses and shorter lifetimes not shown on the figure.

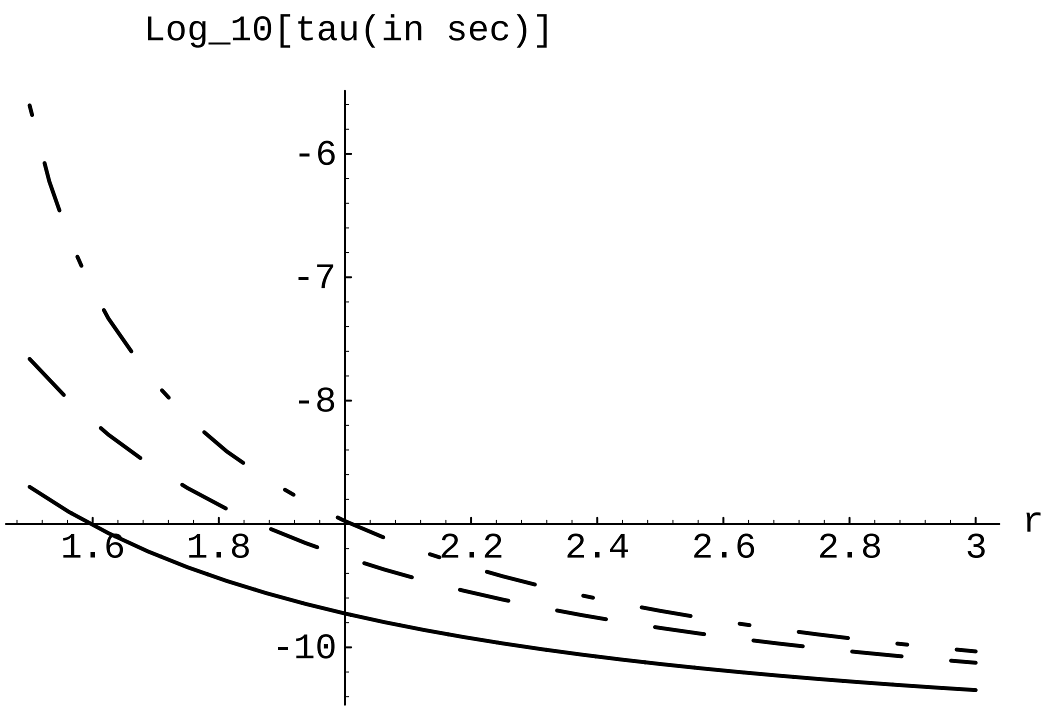

Figure 2: R^0 lifetime in a crude model for three different gluon distribution functions described in the text (solid: F_{ur}, dashed: F_{10}, dot-dashed: F_{nr}) as a function of $r \equiv \frac{m(R^0)}{m_{\tilde{\gamma}}}$, with $m(R^0) = 1.5$ GeV and $M_{sq} = 150$ GeV.

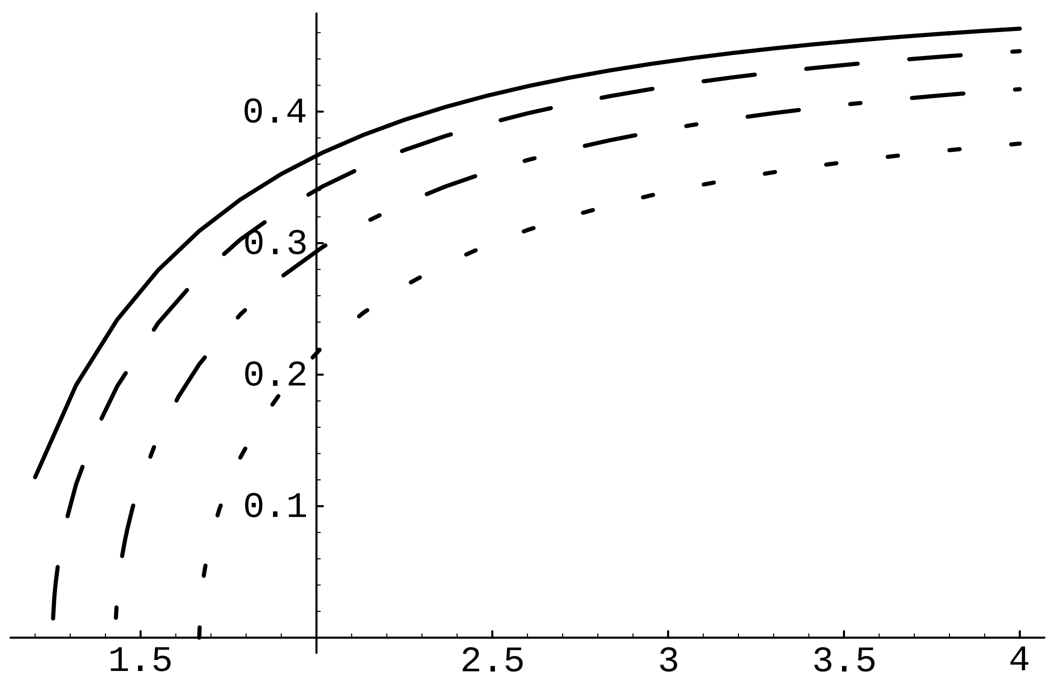

Figure 3: P_h in units of $m(R^0)$ as function of $r \equiv \frac{m(R^0)}{m_{\tilde{\gamma}}}$, for $\frac{m_h}{m(R^0)} = 0.1$ (solid), 0.2 (dashed), 0.3 (dot-dashed), and 0.4 (dotted).